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Hydrology Model Formulation within the Training Range Environmental Evaluation Characterization System (TREECS™)

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Hydrology Model Formulation within the Training Range Environmental Evaluation and Characterization System (TREECS™)

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Final report

Abstract

The Training Range Environmental Evaluation and Characterization System (TREECS™) is currently under development by the Army with varying levels of capability. TREECS™ forecasts the fate of munitions constituents (MC), such as high explosives (HE), within firing/training ranges; it also forecasts the risk of MC transport from surface water to groundwater. The overall objectives are to provide environmental specialists with tools to assess the potential for migration of MC into surface water and groundwater systems and to evaluate range management strategies for protecting human and environmental health. The MC fate models within TREECS™ require hydrologic information as input. A hydrology model was developed to estimate these inputs. This model has been revised several times during the course of TREECS™ development. Although portions of several reports have documented parts of this hydrology model, this report was needed to consolidate the latest version of the model within a single report. The model uses a modified version of the Soil Conservation Service curve number method to compute daily runoff using daily rainfall. Snow build-up and melt is accounted for by using daily precipitation and daily average and maximum air temperatures. Potential evapotranspiration is computed using the Thornthwaite Method. Infiltration is computed from a water balance.

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Preface

This study was funded by the US Army's Environmental Quality and Installations (EQI) Research Program. The work reported herein was conducted by staff within the Water Quality and Contaminant Modeling Branch (WQCMB), Environmental Processes and Effects Division (EPED), Environmental Laboratory (EL) of the US Army Engineer Research and Development Center (ERDC). This report was prepared by Dr. Billy Johnson of the WQCMB and Dr. Mark Dortch under contract to Los Alamos Technical Associates, which was under contract to ERDC.

The study was conducted under the general direction of Dr. Beth Fleming, Director of the EL; Warren Lorentz, Chief, EPED; and Dr. Dorothy Tillman, Chief, WQCMB. Dr. Elizabeth Ferguson was Technical Director of military environmental research, and John Ballard was Program Manager for the EQI Research Program.

Dr. Jeffery P. Holland was Director of ERDC. COL Jeffrey R. Eckstein was Commander. This report is approved for unlimited distribution.

Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters

1   Introduction

Background

The Training Range Environmental Evaluation and Characterization System (TREECS™) is currently under development by the Army and has varying levels of capability. TREECS™ was designed to forecast the fate of munitions constituents (MC), such as high explosives (HE) and metals, within firing/training ranges; it also forecasts the risk of MC transport from firing/training ranges to surface water and groundwater. The overall purpose of TREECS™ is to provide environmental specialists with tools to assess the potential for MC migration into surface water and groundwater systems and to evaluate range management strategies for ensuring protection of human health and the environment. In addition to having utility for the Army, these tools have applicability to other Department of Defense (DoD) services, as well as to state/local agencies and the private sector.

TREECS™ is accessible from the World Wide Web (http://el.erdc.usace.army.mil/treecs/) and has two tiers for assessments. Tier 1 consists of screening-level methods that require minimal data input and that can be easily and quickly applied to assess the potential for MC migration into surface water and/or groundwater at concentrations exceeding protective health benchmarks. Assumptions, such as steady-state conditions, are made to provide conservative or worst-case estimates for potential receptor media concentrations under Tier 1. If a potential concern is indicated by a Tier 1 analysis, then there would be cause to proceed to Tier 2 to obtain a more definitive assessment. The formulations for the Tier 1 modeling approach are presented by Dortch et al. (2009).

Tier 2 assessment methods require more detailed site data and more knowledge and skill to apply, but the methods can be applied by local environmental staff who have a moderate understanding of multi-media fate and transport. The Tier 2 approach allows time-varying analyses of both the solid and non-solid phases of MC with dissolution. A time-varying analysis provides more accurate predictions with generally lower concentrations due to mediating effects of transport phasing and dampening. The Tier 2 modeling approach is described by Dortch et al. (2011). Tiers 1 and 2 focus on contaminant stressors and human and ecological health end point metrics.

Both Tiers 1 and 2 include soil models for predicting the export of MC mass from the area of interest (AOI) — such as the central impact area for firing ranges — to the vadose zone and surface water. The soil models require average annual hydrologic information as input. Consideration is being given to developing an alternative version of the Tier 2 soil model that would use daily varying hydrology. However, presently, average annual hydrology is required, which includes precipitation, rainfall, runoff, evapotranspiration, infiltration, and number of days with rainfall.

A hydrology model was developed to estimate average annual hydrologic inputs required by the TREECS™ soil models. This model resides with the *Hydro-Geo-Characteristics Toolkit* (HGCT), which is a utility under the TREECS™ *Tools* menu for estimating input parameters required by the MC fate models.

Scope

This report documents the formulation of the HGCT hydrology model. This model has been modified several times following its initial development. Although portions of the model formulation have been documented in several different reports, this report consolidates the documentation and also covers the latest version of the model.

General approach

The hydrology model uses a modified version of the Soil Conservation Service (SCS) curve number (*CN*) method to compute daily runoff using daily precipitation. Snow accumulation and melting is accounted for by using daily precipitation and daily average and maximum air temperatures. Potential evapotranspiration (*PET*) is computed using the Thornthwaite Method. Actual evapotranspiration (*ET*) and infiltration are computed from a water balance. The model also computes for each year the number of rainfall impact days and dissolution days, which are both defined later. The model computes the average hydrologic variables for the period of record, and writes out the average annual values for use in the TREECS™ soil models. The remainder of this report describes in greater detail each of these calculations.

2 Model Inputs

The hydrology model requires the following input data:

- Daily precipitation for period of record in units of inches/hour
- Daily mean and maximum air temperature (°C) for period of record
- Starting year for period of record
- Number of years in period of record input
- Average SCS curve number for AOI
- Latitude of study site (AOI)
- Selection of either the northern or southern hemisphere
- Snow evaporation (mm water/day)
- Snow pack lagging factor (dimensionless)
- Snow pack melt factor (mm water/day-°C)
- Selection of either average *CN* or determined *CN* based on previous five days of precipitation (i.e., antecedent moisture condition or AMC)

The period of record for meteorological data (precipitation and air temperatures) should be from a station that is in close proximity to the study site and should consist of at least 20 years of data. The period of record should also be near the time frame being modeled by TREECS™. If future conditions are being modeled, then the meteorological data should be from the most recent years. The Agricultural Research Service (ARS) of the US Department of Agriculture has a Web site that is helpful for finding meteorological data[1].

Guidance on selection of *CN* is available with a HGCT help file. The use of the five-day antecedent moisture condition (AMC) method for determining *CN* is also discussed in the next chapter. Guidance for specifying the snow factors is discussed in Chapter 6 on snow accumulation and melting.

Although input precipitation and most of the model computations are in inches, the output is provided in meters, which is needed by the TREECS™ soil models.

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[1] http://www.ars.usda.gov/Research/docs.htm?docid=19388

3   Calculating *CN* and Runoff

This chapter explains how the hydrology model computes daily *CN* and runoff using a modified *CN* method.

Calculating *CN*

The average *CN* can be determined from cover type, hydrologic condition, and hydrologic soil group. Tabulated values are available within the HGCT help file for selecting *CN* based on cover type, condition, and soil group. Hydrologic soil groups include A, B, C, or D, which describe runoff potential. For example, group A soils are characterized as having low runoff potential with high infiltration rates. Such soils are primarily deep, very well-drained sands and gravels, whereas group D soils have high runoff potential with a very slow infiltration rate when thoroughly wetted. Such soils are primarily clay with a high swelling potential, or soils with a permanent high water table, or soils with a clay layer near the surface, or shallow soils overlying impervious material.

The user has the option of using the average *CN* (*CN2*) for each day or a daily value of *CN* based on the five-day AMC. If the five-day AMC option is selected, the sum of the previous five days of precipitation is used to represent *AMC*, which is used to determine the daily *CN*, which will be *CN1, CN2*, or *CN3*. An AMC I is a dry condition, an AMC II is an average condition, and an AMC III is a wet condition. The values for *CN1* and *CN3* are computed as follows,

$$CN1 = \frac{CN2}{2.3 - 0.013\,CN2} \tag{1}$$

$$CN3 = \frac{CN2}{0.43 + 0.0057\,CN2} \tag{2}$$

The daily *CN* is equal to *CN1* if the *AMC* for the day is less than 0.5 inches. The daily *CN* is equal to *CN3* if the *AMC* for the day is greater than 1.1 inches. Otherwise, the daily *CN* is equal to *CN2*.

Calculating runoff

The daily retention capacity depth, S (inches), is computed from the daily CN value,

$$S = \frac{1000}{CN} - 10 \tag{3}$$

The daily runoff depth, Q (inches), is computed from the standard CN function involving daily precipitation, P (inches), and daily S,

$$Q = \frac{(P-I_a)^2}{P-I_a+S} \tag{4}$$

where I_a is the initial abstraction, which is usually set equal to $0.2S$ in the standard CN method. This modified CN method computes I_a for each day t as follows,

$$I_{a,t} = \max\left(0.0, 0.2S_t - P_{t-1}\right) \tag{5}$$

where t-1 is the previous day. Equation 5 provides a daily update for the initial abstraction based upon the previous day's precipitation. There is runoff for the day if $P_t > I_{a,t}$, and the runoff is computed from Equation 4, or

$$Q_t = \frac{\left(P_t-I_{a,t}\right)^2}{P_t-I_{a,t}+S_t} \quad for \; P_t \geq I_a, otherwise \; Q_t = 0 \tag{6}$$

where $I_{a,t}$ is computed with Equation 5. If $P_t < I_{a,t}$, there is no runoff for the day. There is an additional modification to the standard CN method as follows. If $P_{t-1} > I_{a,t-1}$, and $P_t > I_{a,t}$, then the runoff depth for today, Q_t, equals the precipitation for today, P_t, regardless of the value computed from Equation 6; otherwise, Equation 6 and the rule associated with it prevails. This runoff modification states that if the initial abstraction has been met, all of the precipitation runs off.

As the computations proceed, monthly and yearly average flows are computed for the period of record. Once the yearly average flow has been computed for each year of the period of record, an average annual runoff

computation can be made for the entire period of record. A flowchart showing the runoff calculations is shown in Figure 1. In Figure 1, I is the day counter, and n is the number of days in a year.

Figure 1. Average annual runoff flowchart.
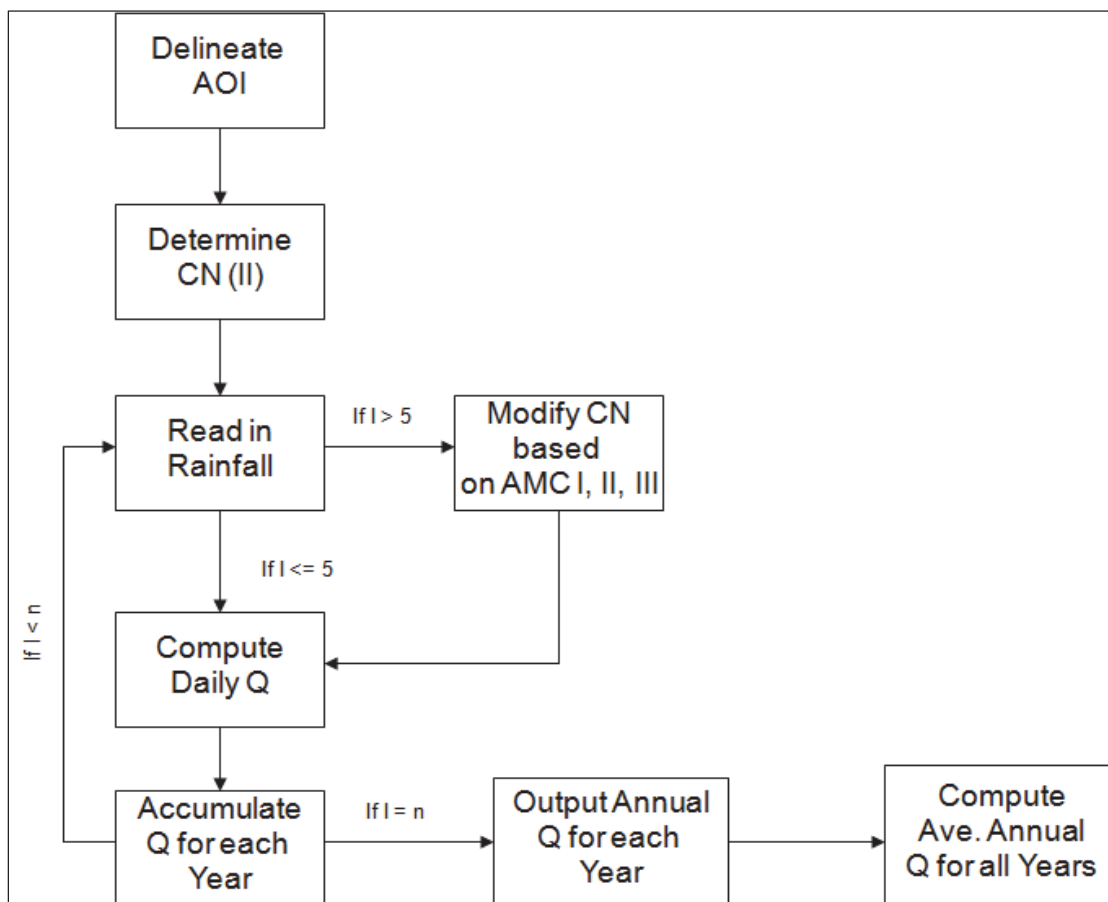
Evaluation of the modified *CN* method for runoff

The modified *CN* method was applied to sub-watershed number 6 of the Goodwin Creek watershed in Panola County, Mississippi. The Goodwin Creek watershed has been used for hydrologic investigations by the ARS. There are long-term records of measured precipitation and runoff for this watershed. The computed annual runoff using the above modified *CN* method is compared with observed runoff in Table 1 for 16 years. The runoff yield is also included for comparison, where yield is the annual runoff divided by the annual precipitation. All runoff was computed with a base *CN* (*CN2*) of 76. A value of 76 is based on fair land condition and Group C soils for land use that consists of 53% pasture, 32% forest, 13% idle open land, and 2% cultivated land.

The observed runoff in Table 1 includes base flow, which is estimated to be about 2 inches per year on average. If the observed runoff is reduced by 2 inches each year, then the average observed yield is 0.35 rather than 0.38. The computed average yield is 0.30 compared to 0.35 observed. Use of a higher *CN* increases the computed runoff and yield. The computed runoff and yield are less (15.1 and 0.25, respectively) than those observed if the standard *CN* method is used.

Table 1. Comparison of observed and computed runoff (Q) and yields for sub-watershed 6 of Goodwin Creek Watershed.

Year	Precipitation, in.	Observed Q, in.	Computed Q, in.	Observed yield	Computed yield
1983	63.3	44.27	28.1	0.70	0.44
1984	62.6	29.85	16.8	0.48	0.27
1985	46.5	24.46	11.3	0.53	0.24
1986	61.7	6.95	8.0	0.11	0.13
1987	56.1	17.11	22.9	0.30	0.41
1988	47.4	10.70	14.1	0.23	0.30
1989	71.0	33.12	25.9	0.47	0.36
1990	63.0	23.59	15.3	0.37	0.24
1991	79.4	41.42	27.8	0.52	0.35
1992	50.0	21.16	16.9	0.42	0.34
1993	42.5	9.6	9.5	0.23	0.22
1996	52.2	11.1	13.3	0.21	0.25
1997	71.7	24.9	15.4	0.35	0.22
1998	43.6	16.6	11.5	0.38	0.26
2002	81.2	28.2	37.8	0.35	0.47
2005	50.1	18.7	12.0	0.37	0.24
Averages	58.9	22.6	17.9	0.38	0.30

4   Calculating Monthly PET

The Thornthwaite Method, which is a heat index method, is used to compute monthly potential evapotranspiration, PET (inches), as described below. The monthly heat index, I_t, is computed from

$$I_t = \left(\frac{T}{5}\right)^{1.514} \tag{7}$$

where T is the mean monthly temperature (degree Celsius). The heat index is computed for each month of each year. Mean monthly PET at 0° latitude is computed from

$$PET(0) = 1.6\left(\frac{10T}{J}\right)^c \tag{8}$$

where

$$c = 0.000000675J^3 - 0.0000771J^2 + 0.01792J + 0.49239 \tag{9}$$

and where J is the sum of the 12 monthly values of heat index I_t for each year. At latitudes other than 0°, PET is calculated by

$$PET = K \times PET(0) \tag{10}$$

where K is a constant for each month of the year, varying as a function of latitude as shown in Table 2.

PET is needed to compute the actual evapotranspiration for each month, ET (inches), which is required for computing the water balance and infiltration.

Table 2. Constant K in Thornthwaite Method.

Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
60ºN	0.54	0.67	0.97	1.19	1.33	1.56	1.55	1.33	1.07	0.84	0.58	0.48
50ºN	0.71	0.84	0.98	1.14	1.28	1.36	1.33	1.21	1.06	0.90	0.76	0.68
40ºN	0.80	0.89	0.99	1.10	1.20	1.25	1.23	1.15	1.04	0.93	0.83	0.78
30ºN	0.87	0.93	1.00	1.07	1.14	1.17	1.16	1.11	1.03	0.96	0.89	0.85
20ºN	0.92	0.96	1.00	1.05	1.09	1.11	1.10	1.07	1.02	0.98	0.93	0.91
10ºN	0.97	0.98	1.00	1.03	1.05	1.06	1.05	1.04	1.02	0.99	0.97	0.96
0º	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10ºS	1.05	1.04	1.02	0.99	0.97	0.96	0.97	0.98	1.00	1.03	1.05	1.06
20ºS	1.10	1.07	1.02	0.98	0.93	0.91	0.92	0.96	1.00	1.05	1.09	1.11
30ºS	1.16	1.11	1.03	0.96	0.89	0.85	0.87	0.93	1.00	1.07	1.14	1.17
40ºS	1.23	1.15	1.04	0.93	0.83	0.78	0.80	0.89	0.99	1.10	1.20	1.25
50ºS	1.33	1.19	1.05	0.89	0.75	0.68	0.70	0.82	0.97	1.13	1.27	1.36

5   Calculating Monthly ET and Infiltration

Daily precipitation and runoff are averaged to obtain monthly values of each. The monthly infiltration rate, I (inches), can be calculated from the monthly water balance involving precipitation, runoff, and evapotranspiration (ET) as follows,

$$I = P - Q - ET \tag{11}$$

Infiltration as defined here is the soil water loading rate available for percolation to the vadose zone and groundwater and/or soil interflow after satisfying runoff and ET.

The monthly ET must be computed before Equation 11 can be used to compute I. If monthly $PET > P - Q$, then $ET = P - Q$, and $I = 0.0$. Otherwise, $ET = PET$ and Equation 11 is used to compute I. The hydrology model computes monthly values of ET and I for each year in the period of record. The model computes the annual values from the monthly values and then computes the average annual values from the annual values for the period of record. The flowchart for these computations is shown in Figure 2.

There are two possible fates of soil infiltration as defined above, percolation to groundwater and soil interflow that eventually returns to surface water, such as base flow in streams. The above approach assumes that there is no soil water deficit that must be satisfied before percolation/interflow can occur. Thus, it is assumed that soil moisture θ (i.e., volumetric soil water content, fraction) is at the field capacity θ_{FC} at all times. During times of prolonged arid conditions, soil moisture may be less than field capacity and soil water must be restored to field capacity before there can be infiltration resulting in percolation/interflow. Revisions to the above approach were considered to account for variations in soil moisture. A description of these revisions and the tests results for them are presented in Appendix A. The test results showed that the above approach was sufficiently accurate compared with the more complex approach described in Appendix A when developing for average annual hydrology. At the time of this report's publication, work was in progress to develop a daily hydrology model to be used for forcing a daily soil fate model to be added to TREECS™. Daily

varying models are being added to allow a more detailed temporal examination of the fate of MC on ranges. The methods in Appendix A are being implemented to compute daily soil water content and infiltration within the daily hydrology model.

Figure 2. Average annual infiltration flowchart.
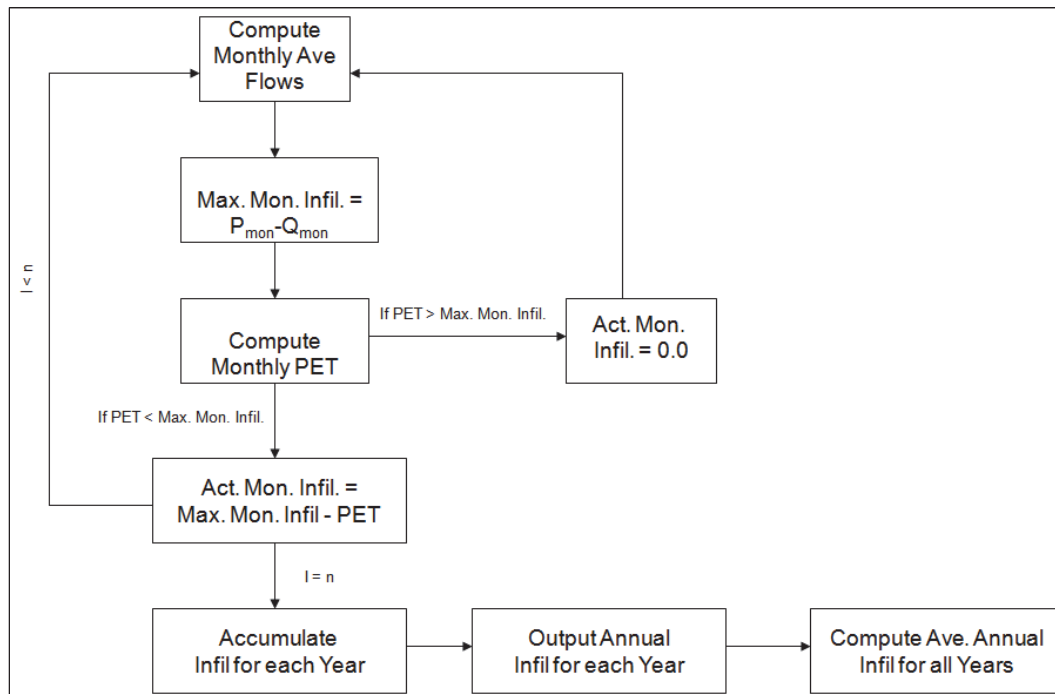
6   Calculating Snow Accumulation and Melting

The hydrology model computes snow accumulation and melting in addition to computing dissolution days and rainfall impact days. A dissolution day is defined as a day where water movement occurs in the soil due to rainfall or snowmelt, thus exposing a solid phase contaminant to dissolution. A rainfall impact day is defined as a day where rainfall occurs and hits the bare ground, extracting MC from the soil pore water. Consequently, the ground must be free of any snowpack for rainfall impact to occur.

The model calculates whether the daily mean air temperature is above or below the freezing level and determines whether precipitation occurs in the form of rainfall or snowfall. The snowfall accumulation balance is

$$Sacc_i = Sacc_{i-1} + S_i - E_i - SM_i \tag{12}$$

where,

$Sacc_i$ = snow accumulation for current day (mm H_2O)
$Sacc_{i-1}$ = snow accumulation for previous day (mm H_2O)
S_i = snowfall for current day (mm H_2O)
E_i = evaporation (sublimation) for current day (mm H_2O)
SM_i = snowmelt for current day (mm H_2O)

From *Handbook of Hydrology*, Maidment (1993), E_i for an 8 hour period at an open site is estimated to be on average = 0.30 mm with a maximum = 0.76 mm and minimum = 0.02 mm. Given that sublimation only occurs during daylight hours, and 8 hours of sunlight are assumed, these values would be the daily sublimation depth.

Snow melting is estimated by,

$$SM_i = b_{mlt} \times sno_{cov} \times \left[\frac{T_{snow_i} + T_{mx_i}}{2} - T_{mlt} \right] \tag{13}$$

where,

b_{mlt} = melt factor (mm H_2O/day-°C)

sno_{cov} = fraction of area covered by snow (0 to 1.0)

T_{snow_i} = snowpack temperature for current day, i (°C)

T_{mx_i} = maximum air temperature for current day, i (°C)

T_{mlt} = base temperature above which snowmelt will occur (°C)

From the Soil and Water Assessment Tool (SWAT)[1], b_{mlt} for rural areas is estimated to vary from 1.4 to 6.9 mm H_2O/day-°C. Modeling assumptions made in the snow calculations are:

- sno_{cov} = 100% (1.0) since we are working with small open areas
- T_{mlt} = 0 °C

Applying these assumptions and recognizing that snowmelt occurs only when $(T_{snow} + T_{mx})/2$ is greater than T_{mlt} (otherwise SM_i is zero), Equation 13 reduces to,

$$SM_i = b_{mlt} \left[\frac{T_{snow_i} + T_{mx_i}}{2} \right] \tag{14}$$

The temperature of the snowpack can be estimated from

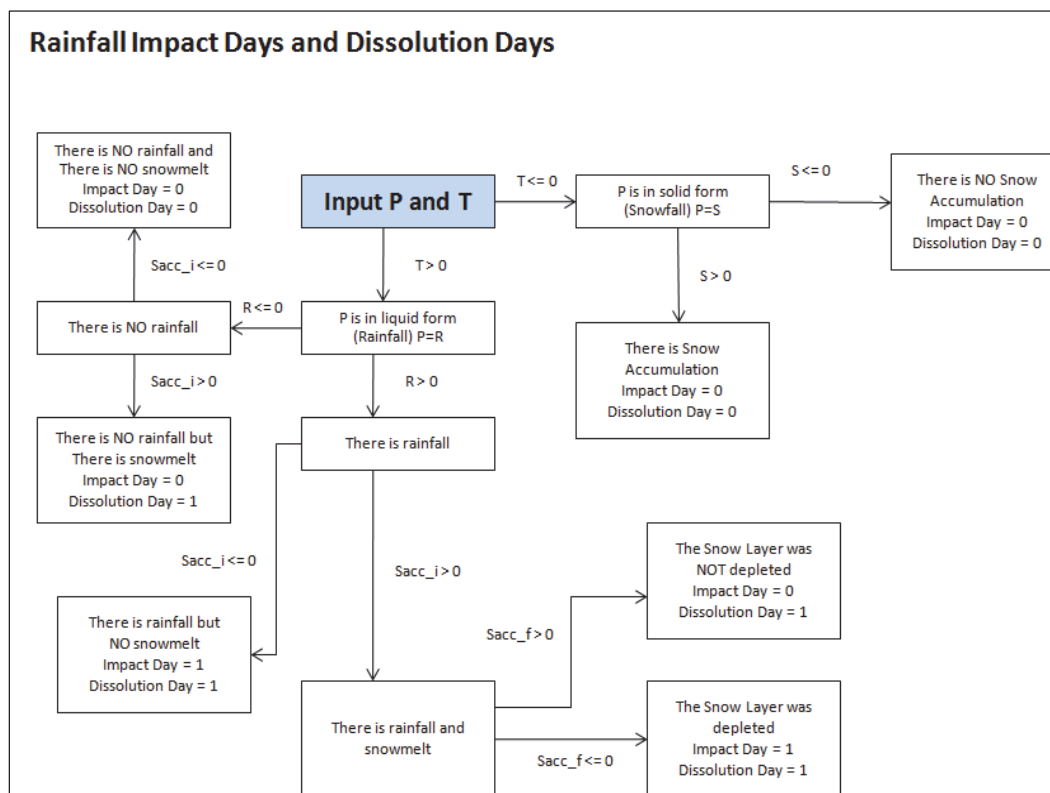$$T_{snow_i} = T_{snow_{i-1}} (1 - l_{sno}) + T_{av} \times l_{sno} \tag{15}$$

where l_{sno} is the lagging factor, which assigns how much weight to put on the previous day's snowpack temperature versus the current day's mean daily air temperature, and T_{av} is the mean daily air temperature (°C). As the lagging factor approaches 1.0, more weight is placed on the current days mean daily air temperature.

The computations for the number of rainfall impact days per year and the number of dissolution days per year are described by the flowchart shown in Figure 3. MC dissolution can occur due to rainfall or snowmelt; however, snow pack must exist for there to be snowmelt. In Figure 3, Sacc_i

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[1] http://swatmodel.tamu.edu/

represents the accumulated snowpack depth at the beginning of the day and Sacc_f represents the accumulated snowpack depth at the end of the day. As the computations proceed, Sacc_f becomes Sacc_i for the following day.

Figure 3. Flowchart for rainfall impact and dissolution days.

Rainfall Impact Days and Dissolution Days

There is NO rainfall and There is NO snowmelt
Impact Day = 0
Dissolution Day = 0

Input P and T

T <= 0

P is in solid form (Snowfall) P=S

S <= 0

There is NO Snow Accumulation
Impact Day = 0
Dissolution Day = 0

Sacc_i <= 0

T > 0

S > 0

R <= 0

P is in liquid form (Rainfall) P=R

There is NO rainfall

There is Snow Accumulation
Impact Day = 0
Dissolution Day = 0

Sacc_i > 0

R > 0

There is NO rainfall but There is snowmelt
Impact Day = 0
Dissolution Day = 1

There is rainfall

Sacc_i <= 0

Sacc_i > 0

The Snow Layer was NOT depleted
Impact Day = 0
Dissolution Day = 1

There is rainfall but NO snowmelt
Impact Day = 1
Dissolution Day = 1

Sacc_f > 0

There is rainfall and snowmelt

Sacc_f <= 0

The Snow Layer was depleted
Impact Day = 1
Dissolution Day = 1

For rainfall impact (i.e., rainfall extracted runoff) to occur, there must be no remaining snow pack. As illustrated in Figure 3, each day's precipitation and mean daily temperature are evaluated along with whether or not a snowpack exists to determine whether or not rainfall impact and/or dissolution occur on that particular day. If the rainfall impact day and/or the dissolution day designation integer are equal to zero, then the module assumes that those processes did not occur that day. If the impact day and/or the dissolution day designation integer are equal to one, then the model assumes that those processes did occur that day and each counter is incremented accordingly. The present version of the TREECS™ soil model uses the average annual number of days of rainfall impact, but it does not use the average annual number of dissolution days; rather, it uses the average annual precipitation. This feature may change in the future if the soil model is modified to allow use of daily hydrology to compute daily MC export from the AOI.

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Appendix A: Evaluation of Revision to the Approach for Computing ET and Infiltration

An alternative approach for computing evapotranspiration *ET* and infiltration *I* are described in this appendix. Tests with this alternative approach were conducted and compared within this appendix to results using the approach described in Chapter 5.

The approach presented in Chapter 5 assumes that there is no soil water deficit that must be satisfied before infiltration (as defined within TREECS™) can occur. Thus, it is assumed that soil moisture θ (i.e., volumetric soil water content, fraction) is at the field capacity θ_{FC} at all times. During times of prolonged arid conditions, soil moisture can be less than field capacity and soil water must be restored to field capacity before there can be infiltration resulting in percolation and/or soil interflow. The following approach was formulated to account for variations in soil moisture.

Description of alternative approach

The time varying soil water depth H_w (in) is computed from $H_w = \theta H$, where H is the soil layer thickness (in), which is constant and has a default value of 0.4 m in the TREECS™ soil model. The time varying soil moisture or water content can be computed from

$$\theta_{t+1} = Max\left(\theta_{t-1} + \frac{P_t - Q_t - ET_t - I_t}{H}, \theta_r\right) \qquad (A1)$$

where the subscript *t* represents the current time period, *t − 1* is at the end of the previous time period, *t + 1* is at the end of the current time period, and θ_r is the residual water content (fraction). All of the other variables in Equation A1 have been defined previously in Chapter 5. The initial water content for the first time period (time step) is assumed to be at field capacity θ_{FC}. The time varying infiltration for the current time period, I_t, can be computed from

$$I_t = Max\left[\left(\theta_{t-1} - \theta_{FC}\right)H, 0.0\right] \tag{A2}$$

Equation A2 is used to compute I_t for use in Equation A1.

Based on a water budget that ignores infiltration for the moment, the calculation of ET_t is as follows,

$$ET_t = Min\left[\left(\theta_{t-1} - \theta_r\right)H + P_t - Q_t, PET_t\right] \tag{A3}$$

Equation A3 does not include infiltration because it is assumed that ET and I_t for the current time period occur simultaneously, and ET is independent of I_t. These assumptions are accurate when the time period, or time step, is sufficiently small, such as a day. Infiltration should not be included in Equation A3 unless infiltration is based on the average water content for the time period rather than water content from the previous time period. Testing showed that including infiltration in Equation A3 resulted in infeasible solutions for ET_t and I_t. All variables are now defined so that the water content computation can proceed forward in time using Equation A1 coupled with Equations A2 and A3.

Testing of Equations A1 – A3 revealed that this approach can be applied using daily or monthly values for inputs *P, Q*, and *PET* and outputs. However, the results are more accurate using daily values since infiltration is computed using the previous period water content rather than the average of water content for the current period, and *ET* does not include infiltration in its calculation. It is noted that when a daily time step is used, the monthly average value of *PET* is divided by the number of days in the month to obtain a daily value, which is constant throughout the month. Using the average water content over the period to compute infiltration greatly complicates the solution of the set of equations. Using a relatively fine time scale, such as a day, negates the need to use average water content and the more sophisticated solution procedure.

If monthly time steps are used for Equation A1 – A3, then the average annual values of *ET* and θ are greater, and the average annual values of *I* are less, compared to using daily time steps. The reason for this trend is due to the fact that Equation A3 does not consider the monthly infiltration loss for computing *ET*, and the calculation of *I* is dependent only on the

previous month's water content rather than the average water content over the month. As noted above, using monthly average water content greatly complicates the solution procedure. Thus, it is recommended that daily steps and inputs be used, unless iteration is used as explained below for monthly time steps.

A more accurate iterative solution can be implemented using monthly time steps and inputs as follows. Equation A2 would be used first to solve for an initial estimate of I_t. Another more accurate form of Equation A3 would be used that includes infiltration loss for the month,

$$ET_t = Min\left[\left(\theta_{t-1} - \theta_r\right)H + P_t - Q_t - I_t, PET_t\right] \qquad (A4)$$

The computed values for ET_t and I_t would be used in Equation A1 to obtain the end of month water content. With this value, the monthly average infiltration would next be updated as follows,

$$I_t = Max\left[\left(\frac{\theta_{t-1} + \theta_{t+1}}{2} - \theta_{FC}\right)H, 0.0\right] \qquad (A5)$$

Equation A5 is a more accurate statement of infiltration than Equation A2. The updated infiltration value would be compared to the previously computed value to check for solution convergence by comparing the relative difference in the two values to a specified tolerance. If the solution has not converged, then the solution process is repeated using the most recent estimate of infiltration (Equation A5) in Equation A4, then applying Equation A1, followed by applying Equation A5 again, and conducting the convergence check. This iterative procedure continues until convergence is reached. This iterative procedure must be performed for each time step.

The only additional input values that are required by the hydrology model are θ_{FC} and θ_r, which can be estimated from soil texture. Field capacity is already addressed within the HGCT via a look-up table. A similar approach can be added for residual water content that is already within one of the help file tables for HGCT. The approach laid out here will allow computation of the average annual soil water volume content rather than assuming it is equal to the field capacity.

Testing of the revised approach

The above revised approach for computing *ET* and *I* was tested within a spreadsheet and compared with infiltration computed with the existing HGCT hydrology model and as described in Chapter 5. Tests were conducted for humid and arid climate conditions.

Daily average and maximum air temperatures and daily precipitation from Panola County, MS, were used to represent humid climate conditions. The Goodwin Creek watershed, which was used to evaluate the modified *CN* approach for runoff, is located in Panola County. Data for the period 1950 – 2008 were used for analysis. Runoff was computed using the modified *CN* approach described in Chapter 3. The humid condition analysis was conducted for two *CN* values, a high and low value of 76 and 60.

The vicinity of Phoenix, AZ, was selected for the arid climate conditions. Daily precipitation and daily maximum and mean air temperatures for the period 1950 – 2008 for Phoenix, AZ, were used. A *CN* value of 40 was used for the arid site.

For each of the three test conditions, the *ET*, soil water content, and infiltration rate were computed using the method proposed above for daily and monthly time increments. The calculations with the monthly time increment were not iterated, however, so the accuracy is expected to be less than that which used the daily time increment. Values of *ET* and infiltration rate were also computed using the HGCT hydrology model, which is based on the method described in Chapter 5. The hydrology model results are monthly values and are compared with the values computed with the spreadsheet using the revised methods described above. Output from the hydrology model also includes *PET* as computed using the Thornthwaite method. The *PET* values are monthly, so they were divided by the number of days in the month to obtain a daily value. The HGCT hydrology model does not compute soil water content; rather, it assumes that soil moisture is at field capacity. For this reason, the field capacity is also shown in Table A1. The results of these tests are summarized in the Table A1 below.

Table A1. Average annual hydrology results in inches or fraction.

Condition and model	Precip.	ET daily step	ET monthly step	Runoff	water content daily step	Infiltration daily step	water content monthly step	Infiltration monthly step	Field cap.
Humid, CN=76	54.72			13.15					0.275
Revised		21.4	22.91		0.23	20.17	0.36	18.55	NA
HGCT		NA	22.38		NA	NA	NA	19.17	NA
Humid, CN=60	54.72			6.9					0.275
Revised		21.7	23.94		0.24	26.13	0.39	23.75	NA
HGCT		NA	23.41		NA	NA	NA	24.39	NA
Arid, CN=40	8.45			0.032					0.09
Revised		5.9	6.53		0.046	2.52	0.089	1.88	NA
HGCT		NA	6.26		NA	NA	NA	2.15	NA

The results in the above table indicate that using a monthly time step results in substantially greater water content and lower infiltration compared with using daily values. It is emphasized that the calculations with a monthly step did not include any iteration as recommended in the above approach for monthly steps, which requires using Equations A4 and A5 rather than A2 and A3. Thus, it is recommended that the results for water content and infiltration using a daily step be compared with field capacity and infiltration results from HGCT. In all three test cases, the computed water content is lower than the field capacity. TREECS™ presently assumes that the soil water content is equal to field capacity. Additionally, in all three test cases, the computed infiltration is slightly greater (5 to 17 %) for the revised method compared with the results computed by the HGCT hydrology model.

Given the relatively small amount of improvement provided by using the revised methods described in this appendix compared with using the methods that presently exist within the HGCT hydrology model and as described in Chapter 5, it is recommended that the present form of the HGCT hydrology model be used for computing *ET* and *I* for average annual hydrology. The slight amount of improvement in the accuracy of the infiltration (which is generally on the order of 1 to 2 inches per year or less) is probably offset by the inaccuracy in estimating other variables that

affect infiltration, such as runoff, *PET*, field capacity, and possibly even precipitation.

Percentagewise, there is more improvement provided by the revised methods for estimating water content than for estimating infiltration, especially for arid conditions where average annual water content is about half of field capacity. TREECS™ validation test cases (Dortch 2012) were rerun using field capacity less 0.05 for water content as input. These tests showed that model results for receiving water and sediment concentrations were altered by no more than 4% and, in most cases, the results were indiscernible. Given the uncertainty in other model inputs, there is little merit in modifying the hydrology model to calculate average annual water content.

However, as noted in Chapter 5, capabilities are being added to TREECS™ allowing for daily varying hydrology and MC fate on ranges. This daily version of the hydrology model will include the above approach for computing daily soil water content, ET, and infiltration. The option is being implemented to use either the explicit (no iteration) or implicit (with iteration) solution approaches as described above. Since daily hydrology will be forcing the daily soil MC fate model, inclusion of the more precise procedures above is merited.

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14. ABSTRACT
The Training Range Environmental Evaluation and Characterization System (TREECS™) is currently under development by the Army with varying levels of capability. TREECS™ forecasts the fate of munitions constituents (MC), such as high explosives (HE), within firing/training ranges; it also forecasts the risk of MC transport from surface water to groundwater. The overall objectives are to provide environmental specialists with tools to assess the potential for migration of MC into surface water and groundwater systems and to assess range management strategies for protecting human and environmental health. The MC fate models within TREECS™ require hydrologic information as input. A hydrology model was developed to estimate these inputs. This model has been revised several times during the course of TREECS™ development. Although portions of several reports have documented parts of this hydrology model, this report was needed to consolidate the latest version of the model within a single report. The model uses a modified version of the Soil Conservation Service curve number method to compute daily runoff using daily rainfall. Snow build-up and melt is accounted for by using daily precipitation and daily average and maximum air temperatures. Potential evapotranspiration is computed using the Thornthwaite Method. Infiltration is computed from a water balance.

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